Cognitive Models for Training Simulations

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Chapter 1

Introduction

1.1 Motivation

Military organizations tend to operate in highly uncertain and dynamic environments, and therefore require competent staff that acts adequately in any emerging situation. Competent staff members are formed and maintained by training them in their task execution. However, the very nature of military missions makes it hard to set up real-world training. Practical issues are that the pace of military missions is often too low for training, while the level of danger is often too high. In addition, logistical issues play a role: mimicking a military mission in the real world requires many people and a large amount of money.

Fortunately, scenario-based simulator training is considered an appropriate alternative approach for training decision-making in complex environments (Oser, 1999). A main requirement for the success of simulator training is that it *correctly represents these aspects of the real world that are necessary to achieve the training objectives.* Which aspects these are varies from task to task. For example, when the simulated environment is used to train kite flying, it is important to represent wind and its influence on the kite, while these aspects are not required for training kite building.

1.1.1 Human Behavior Representation

The importance of validly representing the behavior of other humans in the simulated environment also varies between tasks. To train kite flying this is not important, nor is it for tasks in the process industry. But for a task like car driving, it is required that a person is trained in the interaction with road users in addition to the main driving task. Other tasks, like leading a team, solely consist of human interaction.

For military tactical decision-making the behavior of other humans, e.g., team members and opponents, is an important aspect. In order for simulator training to be an alternative for real-world training this behavior must be validly represented, i.e., have observational fidelity. Unfortunately, it can be hard to establish and hence to model which behavior is valid in any situation. To ensure that the simulated humans behave in a realistic way, Subject Matter Experts (SMEs) are often used to play these roles in tactical training scenarios. SMEs have the expertise to take the situational context into account and can use this understanding to representatively play a role in the training scenario. In addition, SMEs display varied behavior. This is required for training: when trainees are exposed to predictable behavior they might simply learn to 'play' with or against a specific entity, instead of learning their task. Moreover, SMEs are able to explain their behavior. This is a capability frequently used in the part of training called *after action review*, in which the trainee's behavior is critiqued.

Unfortunately, the logistical issues of real-world training, namely the large amount of money and organizational effort involved, also hold for simulator training when the attendance of SMEs is required. It would be highly beneficial when instead of SMEs computer programs could play roles in training simulations. This software should possess the capability of SMEs to respond in valid and varied ways to emerging situations.

1.1.2 Software Agents

Software that is capable of displaying autonomous behavior in interaction with other entities is generally referred to as an *agent*. This term is deduced from the Latin verb *agere*: to act. Agents are entities that exist in a world, and can observe, reason, and perform actions in that world (Russell and Norvig, 2003). What further constitutes agency has been the topic of much discussion (Franklin and Graesser, 1997).

Wooldridge and Jennings (1995) distinguish two general usages of the term agent and define two notions of agency. Because their first notion is relatively uncontentious, they call it the *weak* notion of agency. Their second notion is called *strong* as it is more contentious, and requires the software to satisfy additional constraints. The weak notion of agency defines an agent as a system that has the following properties: i) autonomy ii) social ability iii) reactivity and iv) pro-activeness. They state that for a system to fit into the stronger notion of agency it should further incorporate one or more concepts that are applicable to humans, for example: v) mentalist notions (beliefs, goals, plans, and intentions) vi) emotions vii) mobility viii) rationality or ix) adaptability.

Since no clear definition of agency exists that specifies its functionalities, many agent subclasses have emerged. Most distinguishable is the class of rational agents, which contains agents that only act in ways that help them achieve their goals and never in a way that prevents this achievement. Although this property is very suited for developing software for a clear goal, it is not representative for human behavior.

1.1.3 Cognitive Biases

Task experts are expected to behave in a rational way. Unfortunately, there exist distinct and replicable ways in which human judgment and decision-making differs from decision-making based on rational choice (Tversky and Kahneman, 1974). It is generally acknowledged that these differences stem from the fact that human cognition has fundamental limitations (see, e.g., Miller, 1956; Kahnemann, 1973). These cognitive limitations force humans to apply simplified rules and heuristics while processing information for judging or decision-making. These simple rules often work well and are even regarded as adaptive given their ecological validity (Gigerenzer et al., 1999). However, when the outcome of such a simple rule deviates in a structural way from the rational outcome, it is called a cognitive bias.

Human decision-making is subject to a wide variety of cognitive biases (Wickens and Flach, 1988; Perrin et al., 1993). Such cognitive biases influence the quality of human decision-making and are found to arise especially under stress conditions (Baron, 2000). Military missions are generally stressful, and the decision-making processes of military experts are structurally affected by biases (Fewell and Hazen, 2005). It is therefore important to train military personnel in recognizing and dealing with their own biases, as well as with the biases displayed by their team mates.

1.1.4 Cognitive Models

For training military personnel in tactical decision-making in a simulated environment, it is important to validly represent the behavior of other humans present. Human behavior representation has a long history. Much work exists in Cognitive Science and Artificial Intelligence on the modeling of specific aspects of human behavior, such as vision, concept formation, rule learning, planning and motor control. Other work focuses on generic mechanisms and representation forms that may be useful for modeling multiple human behavioral aspects. Examples are logic engines, condition-action rules, neural nets and genetic algorithms (see, e.g., Russell and Norvig, 2003).

Several researchers have focused on determining the general characteristics of human behavior, with the goal to establish a so-called unified theory of cognition (UTC). A UTC is a single set of mechanisms that accounts for all aspects of cognition (Newell, 1990). These mechanisms are supposed to be constant over time, and across tasks and application domains. When these mechanisms are implemented in software they form a *cog-*

nitive architecture. Cognitive architectures constitute a fixed set of processes, memories and control structures that define their underlying theory about human cognition (Lewis, 2001).

Cognitive architectures can be used to build specific cognitive software agents. A cognitive software agent is formed by adding task-specific knowledge in the form of facts and rules to the cognitive architecture, which results in an executable cognitive agent model. Because theories of cognition differ, the behavior of a cognitive software agent is influenced by the architecture it is implemented in (Jones et al., 2007).

In this dissertation we define cognitive software agents as software agents with human-like cognitive capabilities. Note that this definition does not specify the required type of cognitive capability, or the way in which it should be implemented. Moreover, we treat executable agent models as synonymous to software agents: a cognitive (software) agent is equal to an *executable* cognitive agent model. A cognitive agent model always incorporates a cognitive model, but again, it is not specified how, or which type. A cognitive model by itself does not need to be executable, or form a complete agent model; many cognitive models only model a specific aspect of human behavior.

There is growing conviction and evidence that cognitive software agents can validly play roles within simulated environments instead of humans, and thus aid (military) training (Pew and Mavor, 1998; Ritter et al., 2003). However, much work remains to be done, e.g., on the incorporation of episodic memory in agents and on the reusability of the knowledge they embed (Langley et al., 2006).

1.1.5 Agent Requirements

In the previous sections we have implicitly discussed a number of requirements for cognitive software agents that play a role in a simulated training environment: they need to be able to show behavior that has observational fidelity, this behavior needs to vary, and they should be able to display biased behavior. In addition, it would be useful if they could explain their own behavior. These requirements directly correspond to the capabilities of Subject Matter Experts. However, the capability of SMEs to display varied behavior also contains a didactic disadvantage: the variability of the SMEs' behavior in combination with limited training time makes it hard to ensure that the trainee reaches all the training objectives, and therefore that he or she completes every stage of training.

It is desired that the behavior of simulated entities in training simulations is in service of the training goals. This is likely when instructors, who are SMEs that also possess didactic knowledge, play the roles required for a specific training scenario. Unfortunately, it is not realistic to require an instructor for each role. A second option would be that instructors could constrain the behavior of simulated entities to ensure that their behavior is in service of the training objectives. Although it is hard to tune the behavior of humans, this is possible for cognitive software agents whose behavior is programmed.

Cognitive software agents that can validly represent human behavior offer a solution to the organizational effort involved in SMEs enabled simulator training. Cognitive agents whose varied behavior is tunable by an instructor offer a solution to the didactic issue of having SMEs play roles within a training scenario. To ensure cognitive agents also cut back expenses, the costs of developing them should not be too high. This entails that it should be avoided that for every new domain, task, or even simple scenario a new agent has to be built from scratch. Therefore, we take a component-based approach to designing cognitive agent models. This approach facilitates the reuse of the knowledge captured in the developed components.

1.1.6 Feedback Generation

The success of scenario-based simulator training depends not only on the valid representation of the relevant aspects of the task environment, but also on *the generation of feedback on the trainee's behavior* (Bosch and Riemersma, 2004). Usually human instructors monitor the trainee, evaluate the appropriateness of his or her behavior, and provide feedback. The use of instructors to generate feedback suffers from the same disadvantages as the use of SMEs or instructors to generate human behavior. Besides the logistic issues there is a didactic issue of variability in feedback between instructors. Although varied feedback is not necessarily harmful and possibly even useful, the military organization is keen on providing training in a structured way to ensure trainees get a comparable education.

It would be beneficial if software agents could not only replace human role players, but also human instructors. The latter is the focus of the research field on intelligent tutoring systems that combines knowledge and theories from Educational Science with methods from Artificial Intelligence. Intelligent tutoring systems comprise the knowledge of a domain expert, and use this knowledge to generate instructions and feedback to a trainee so he or she can learn about the domain (Polson and Richardson, 1988).

Most intelligent tutoring systems developed train procedural or simple declarative tasks. These tasks are typically well-defined, and feedback is based on expert knowledge in the form of rules or constraints that can unambiguously determine the correctness of certain actions in certain states. More challenging is the generation of feedback on trainee behavior in complex tasks like tactical decision-making. In such tasks the correctness of a certain action in a certain state can seldom be determined in a straightforward way. In general other aspects of the behavior should be taken into account for generating feedback, like the choices that were considered, or the sequential behavior.

Human instructors deal with the difficulty of diagnosing the task performance of a trainee by his or her visible actions by forming a mental model of the cognitive processes of the trainee. Subsequently, they base their feedback on this cognitive model. In order for a software agent to generate feedback on the (un)observable behavior of a trainee in a similar way, it should be able to reason about a trainee's cognitive processes. This can be done by forming a cognitive model of the trainee.

Furthermore, due to their years of training experience, instructors have a good sense of the kinds of errors trainees tend to make. Some of these errors are a direct result of cognitive biases. When the behavior of a trainee coheres with one of these wrong behaviors it is likely that the instructor classifies it as that specific error. Next, the instructor can provide feedback based on this match. In order for a software agent to recognize trainee behavior as a typical (cognitive) error, it should be able to reason about typical biased cognitive processes and their outcome. This can be supported by incorporating several (biased) cognitive models.

1.1.7 Synopsis

Although simulator training offers an alternative for real-world training of complex military tasks, currently such training depends on the availability of instructors and subject matter experts. The study presented in this dissertation aims at contributing to the development of (cognitive) software agents that can replace these humans. The agents that are to play a role in the simulated environment need to incorporate a cognitive model to do this in a valid, human-like way. The agents that are to give feedback on a trainee's task performance in a simulated environment need to be able to form and reason about cognitive models. Therefore this dissertation is titled *Cognitive Models for Training Simulations*. The ultimate goal is to replace all humans currently involved in simulator training, so that trainees can train by themselves at any time.

1.2 Research Objective

1.2.1 Research Focus

Many researchers share our interest in the modeling of human behavior in order to replace humans. However, this interest is not always focused on the modeling of the *cognitive* capabilities of humans. For example, most tasks at assembly lines are nowadays automated and performed by machines instead of humans. For such cases it is mainly important to model the human ability to perform specific manual operations. This dissertation focuses on research that concerns the modeling of internal, cognitive aspects of humans and not on the modeling of external aspects, such as the visual system and motor behavior.

The modeling of cognition commonly services one of the following two goals. The first goal is to better understand human cognition. A model of a cognitive process is made with the aim to gain insight in the underlying mechanisms of that process. When the results and the behavior of the model strictly cohere with that of the cognitive process it aims to model, it can be deduced that the mechanisms underlying this process are accurately modeled. This method is also described as 'the logic of simulation' (Gilbert and Troitzsch, 1999), see Figure 1.1.

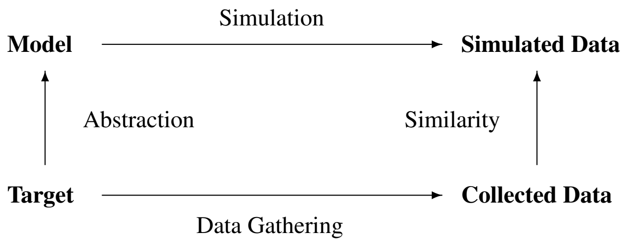

Figure 1.1: The logic of simulation as a method (Gilbert and Troitzsch, 1999)

The second goal of modeling cognition is to make artificial systems operate more intelligently, so that they can replace humans. For this it is not attempted to accurately model the mechanisms underlying cognition, but to capture specific characteristics. It is usually not the goal to develop a model that can replace humans in all aspects and in all circumstances: a model is developed to replace a human for a specific task. For that reason, the model does not need to represent all mechanisms underling human behavior, but only those mechanisms that are relevant for the particular task, and at a suitable level of abstraction.

These two separate goals closely follow the division made by March and Smith (1995) between *natural* and *design* science. Natural science is concerned with 'explaining how and why things are' and as such aims at understanding reality. Design science is concerned with 'devising artifacts to attain goals', and as such attempts to create things that serve human purposes.

This dissertation focuses on the development of software agents that can replace humans for a specific goal: for playing the role of a human in a training simulation, or for generating feedback on the task performance of a human trainee. This research can thus be viewed as a typical example of *design* science. Our aim for modeling cognition is not to understand it better, but to equip an artificial system, the software agent, with methods and techniques so that it can possibly replace a human.

1.2.2 Research Questions

The main research objective of this study is the modeling of cognitive agents that can generate human-like behavior for roles in training simulations of military tasks. We are interested in the modeling of a wide variety of human-like behavior, and do not only want to model behavior that can be considered expert behavior. In stressful situations, frequently faced by the military, behavior is often not rational due to the emergence of biases that influence decision-making. Biases do not always occur in the same form and amount: their occurrence is strongly affected by task circumstances. This makes it important to model biased behavior in training simulations, so a trainee can learn to recognize and deal with biases. Therefore, the main research question of this study is:

Q1: How can a cognitive agent display human-like behavior with a varying degree of biasedness?

This question embeds multiple aspects. First, it has to be established how an agent can display expert behavior. Next, it has to be determined which cognitive processes can become influenced by biases, how biases influence these processes, as well as when they do so. In the course of the research we narrowed this broad research question down to investigating whether it is possible to model human-like behavior with a varying degree of biasedness by extending qualitative models with quantitative elements.

In addition to this main research question, we have explored two supplementary research questions. It was mentioned that the modeling of the agents should happen efficiently to reduce their development costs, which spurs a component-based approach to the modeling of agents. In order to reuse components it is required that their properties are described in such a manner that at a later stage it can easily be determined whether they are suitable to be reused for a particular purpose. We hypothesize that it is a good idea to tag cognitive agent components with the cognitive capabilities they embed. However, there does not exist consensus on a taxonomy of cognitive capabilities, or on a way to describe them. Therefore, we start to investigate the following research question:

Q2: How can cognitive agent capabilities be described?

Besides the modeling of cognitive agents that display human-like behavior, we would also like to model agents that can generate feedback to a trainee in training simulations of military tasks. Previously, we explained that for an agent to generate feedback on trainee behavior in complex tasks, it needs to be able to reason about the cognitive processes of that trainee. This is required because the feedback for such tasks should be at the level of the cognitive processes of the trainee, and not solely on the factual outcome of his or her behavior. Therefore, we explore the research question:

Q3: How can an agent generate cognitive feedback on a trainee's task behavior?

In this dissertation we particularly investigate whether it is possible to generate cognitive feedback to a trainee on his or her task behavior by comparing it to the behaviors generated by expert and deficient task models.

1.3 Research Approach

Here we elaborate on the research approach followed in this study. In particular, we introduce the regulative research cycle, and apply it to our research objective.

1.3.1 Research Methodology

Previously, we introduced the work of March and Smith (1995) who divide research into *natural* and *design* science. March and Smith consider research to be *natural* science when it is concerned with explaining how and why things are, and as such aims at understanding reality. They view natural science as consisting of two activities: *discovery* (the process of generating or proposing scientific claims), and *justification* (includes activities by which such claims are tested for validity). These activities resemble phases within the methodological model known as the *empirical* cycle (Groot, 1969), which is commonly used to develop a theory within a dominant paradigm.

The empirical cycle includes the following phases: 1) *Observation*: empirical facts are collected; 2) *Induction*: hypotheses are formulated on the basis of the observed facts; 3) *Deduction*: on the basis of those hypotheses, some specific predictions are formed; 4) *Testing*: these predictions are empirically tested by collecting new data; 5) *Evaluation*: the results are evaluated on their theoretical validity. In this last phase new ideas are often generated that can be examined by a new empirical cycle.

March and Smith (1995) consider research to be *design* science when it is concerned with devising artifacts to attain goals, and as such attempts to create things that serve human purposes. They state that design science also consists of two basic activities, namely: *build* (the process of constructing an artifact for a specific purpose), and *evaluate* (the process of determining how well the artifact performs, which is complicated by the fact that performance is related to intended use). These two activities resemble phases within the methodological model known as the *regulative* cycle (Strien, 1997). This methodological model is more practice oriented, and focuses on solving an individual problem in particular circumstances.

The regulative cycle includes the following phases: 1) *Problem definition*: identification of a discrepancy between an actual and a normative situation; 2) *Diagnosis*: clear formulation of the problem; 3) *Plan*: development of a solution for the identified problem; 4) *Intervention*: implementation of that solution; 5) *Evaluation*: testing whether the proposed solution has narrowed the gap between the actual and normative situation. The last phase may identify new or remaining problems that can be examined by a new regulative cycle.

The regulative cycle is normative in the sense that the development of a plan is guided by an objective derived from the problem under consideration. This makes it applicable to design-oriented research, and stresses what Simon (1967) already expressed:

> "The engineer and more generally the designer, is concerned with how things ought to be - how they ought to be in order to attain goals, and to function (...) With goals and 'oughts' we also introduce into the picture the dichotomy between normative and descriptive. Natural science has found a way to exclude the normative and to concern itself solely with how things are (...) Artificial things can be characterized in terms of functions, goals and adaptation."

The research described in this dissertation is a clear example of *design* science and therefore, the research method embodied by the regulative cycle is applicable.

Although the empirical and the regulative research cycle are presented as separate processes, they are inevitably connected. Theories that are the result of the empiric cycle are often used within the first phases of the regulative cycle. Because of this application of theory into practice, feedback from the intervention and evaluation phases of the regulative cycle can in return be used to further develop theories by the empirical cycle.

1.3.2 Regulative Research Cycle

The aim of our study is to contribute to the development of software agents that can fulfill tasks within simulator training of military tasks that are currently fulfilled by humans. This general research objective emerged from the first phase of the regulative cycle, namely the *problem definition* (1). In the first section of this chapter we identified a clear discrepancy between the actual situation in which trainees are trained for open and complex tasks, and the desired situation. The actual situation is that other humans are required for such training which induces high costs, great organizational effort, and undesired training variability. The desired situation is that trainees can train by themselves because the humans are replaced by software agents. For this, agents 1a) should be able to show valid behavior in a simulated task environment which can be tuned to be more or less biased, and 1b) need to be affordable and as such be based on components that can be found for reuse. In addition, agents 1c) should be able to give feedback on (biased) trainee behavior in simulated task environments.

The *diagnosis* (2) of the problem that becomes explicit throughout this dissertation splits the problem up in three main issues: no suitable methods exist for 2a) modeling various required behaviors of cognitive agents in a way that that behavior is valid, varied and has a varying degree of biasedness, nor for 2b) describing the developed agent components so that they can be found for reuse. Furthermore, 2c) no method exists that enables an agent to generate feedback on (biased) trainee behavior in open, dynamic, complex tasks.

Therefore our *plan* (3), reflected in the research questions listed in Section 1.2.2, is to 3a) develop methods with which various required behaviors of cognitive agents participating in a military simulation can be modeled, and to 3b) investigate how the capabilities of developed agent components can be described. Moreover, we plan to 3c) develop a method which enables an agent to generate feedback on trainee behavior for open, dynamic, complex tasks.

In phase (4), *intervention*, the developed methods are used to 4a) implement cognitive agents that show (biased) behavior within a simulated environment, to 4b) describe various capabilities of cognitive agents, and to 4c) implement an agent that generates feedback on trainee behavior in a simulated environment.

In the final *evaluation* (5) phase it is tested whether our study aids in narrowing the gap between the actual and normative situation. In other words: whether it contributes to the future modeling of agents that 5a) can show valid, human-like behavior with a tunable degree of biasedness in complex tasks in simulated environments, 5b) are affordable because they are based on components that can be found for reuse, and 5c) can give feedback on (biased) trainee behavior in complex tasks in simulated environments.

This regulative cycle is the major research cycle of the study described in this dissertation. In it multiple sub-cycles are embedded, each investigating a sub-problem of a non-existing method to model a required agent behavior (2a).

These regulative sub-cycles start in general with a *problem definition* in the form of: there exists a discrepancy between the aspects of human behavior that existing methods can model and the aspects that are required for this specific (military) task. To establish such a discrepancy, first the cognitive properties of human behavior that are required to validly fulfill that specific task are determined. At the same time it is determined which cognitive properties current approaches can model. When a discrepancy is found, the *diagnosis* states clearly which cognitive properties the to-be-developed method should be able to model. Next, in the *plan* phase, inspiration for a solution to the problem is drawn from theories about the underlying mechanisms of the required human behavior developed by natural science. The solution is first logically formalized and then, in the *intervention* phase, implemented for a specific case. These implementations vary from executable models for simple abstract tasks, to models implemented in existing cognitive architectures for realistic tasks. Next, these agent implementations are *evaluated*. These evaluations vary due to the variety in implementations. They range from checking whether the agent's behavior displays the cognitive properties established in the diagnosis phase, to checking its face validity by consulting subject matter experts.

1.3.3 Related Research Disciplines

From this regulative research cycle it follows that many research disciplines are relevant to this study's research objectives. Below the major ones are listed, together with a short description of how they contribute.

- **Cognitive Science** - provides unified theories of cognition as well as many specific theories on cognitive processes like planning, belief revision, attention and stress.
- **Computer Science** - provides a computational means to formalize and test the theoretical models of cognitive science. Various unified as well as specific computational cognitive models have been developed. In addition, computer science provides methods to describe software and its working.
- **Artificial Intelligence** - provides various techniques for modeling intelligent behavior. AI draws its inspiration from human intelligence, however, its techniques are not necessarily cognitively valid or plausible.
- **Educational Science** - provides insight in how humans learn and offers guidelines concerning the kinds of training environments and types of feedback that are suited for training specific tasks.

1.4 Research Scope

In this section we discuss the scope of the study described in this dissertation. We start with the context in which the study was conducted, and then elaborate on the domain it focuses on. Next, we introduce the military task that is used throughout this study as example of which the training can be supported by software agents. As an outlook, this section lists the requirements for agents capable of executing or providing feedback to the example task.

1.4.1 Research Context

The study described in this dissertation was conducted in a cooperation between the Agent Systems Research group of the Vrije Universiteit Amsterdam and the Training and Instruction department of TNO Human Factors. TNO Human Factors is a business unit of TNO Defense, Security and Safety, which is one of the five core areas of TNO, the Netherlands Organization for Applied Scientific Research. The study took place in parallel to the TNO research program **Cognitive Modeling** (V524), funded by the Netherlands Defense Organization. This program focuses on 'Cognitive Models of Tactical Decision-Making' and incorporates three projects: *Training*, *Decision Support* and *Agent Architectures*.

Within the *Training* project cognitive models are developed for training purposes; it is investigated whether such models can make training more realistic, more traceable, and more cost-efficient. The *Decision Support* project develops cognitive models for decision support; it investigates how such models can be used to deliver adaptive support, tailored to the operator's decision-making process. *Agent Architectures* is a coordinating project; it investigates and develops architectures required for implementing the cognitive models into intelligent agents, and for linking these agents to simulation systems.

Predating the Cognitive Modeling research program, the researchers within the Training and Instruction (T&I) department did not have much knowledge about the development of cognitive models and their implementation in software to form intelligent agents. Their main expertise was the training of people, especially in complex decision-making tasks. Researchers within the Agent Systems Research (ASR) group did not have experience with this type of training. However, they did have many years of experience with designing intelligent agents, and in more recent years also in cognitive modeling (Bosse, 2005). One of the accomplishments of the ASR group has been the development of component-based system design method DESIRE that explicitly models agents, their environment, and their interaction, during different phases of design (Brazier et al., 2002).

By conducting this study in a cooperation between a university and a research institute, the feedback cycle embedded in the regulative research cycle was fostered. In the previous section we introduced the regulative research cycle. We elaborated on how the application of theory into practice by the intervention phase can, through the final evaluation phase, lead to feedback on new or remaining problems that can be examined by a new regulative cycle. In this study, we mainly developed mechanisms and techniques in cooperation with the university, and subsequently implemented and evaluated them in cooperation with the research institute. The experiences gained were used to formulate new requirements for the cognitive agent models, which were succeedingly investigated by a new research cycle. As a result of the cooperation, the T&I department of TNO gathered knowledge concerning modeling (cognitive) agents, while the ASR group got inspired by the possibilities to use cognitive models to support humans, not only for training but also for decision support.

1.4.2 Research Domain

The research domain of the Cognitive Modeling program is *Tactical Command*, which is defined by the Oxford Essential Dictionary of the U.S. Military as:

> “The authority delegated to a commander to assign tasks to forces under his or her command for the accomplishment of the mission assigned by higher authority.”

A commander ‘assigning tasks to forces under his command to accomplish mission success’ is executing a tactical decision-making process. A concept often applied to describe the decision-making process in military operations is the OODA loop, which stands for Observe, Orient, Decide and Act. The OODA loop, also called Boyd cycle, was developed by USAF Colonel John Boyd, and describes human decision-making as a recurring cycle of observe-orient-decide-act, see Figure 1.2.

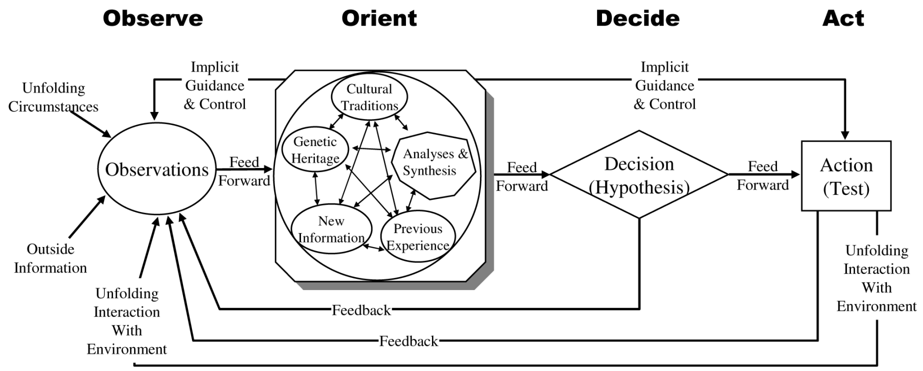

Figure 1.2: John Boyd’s OODA loop (adapted from Boyd (1996))

The main focus of the research program and this study lies on the **Orient** part of the OODA-loop, which denotes the commander’s assessment of the current situation. However, the modeling of the entire loop is investigated since orientation is intertwined with observing the environment, with making decisions, and with acting based on the assessed situation. In addition, all these processes need to be modeled to form an executable agent.

1.4.3 Research Task

The Orient part of the OODA-loop is aimed at achieving situational awareness (SA), which is a state of knowledge. Endsley (1995) defines SA as:

> “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future”.

Another definition is given by the US-Army (2002) who defines SA as:

> "the ability to maintain a constant, clear mental picture of relevant information and the tactical situation. This picture includes knowledge of both the friendly and threat situations and of relevant terrain".

The process of achieving, acquiring, or maintaining SA is referred to as *situational assessment* (Endsley, 1995). It is generally recognized that lacking SA, or having inadequate SA, is one of the primary reasons for decision-making errors. Therefore, training students in achieving good SA, i.e., in the situational assessment task, is a spearhead of the Netherlands Defense Organization.

Military tactical experts achieve Situational Awareness in a quick and accurately way by using their large knowledge base of tactical patterns gained over time. Zsambok and Klein (1997) show that experts use this accumulated experience when making a decision: they base their decision on recognized pattern similarities between the actual decision-making situation and stored situations.

In order to train students to become tactical experts, they should be engaged in intensive practice facing a wide variety of situations. This enables them to build up experience in achieving SA, and to expand and sophisticate their knowledge base of tactical patterns. This is an important motivation for our requirement that the cognitive agents that are to display human-like behavior in training simulations, should be capable of displaying *varied* behavior.

TNO's Cognitive Modeling program is of interest to all three major defense areas: the Royal NetherLands Navy (RNLN), Army, and Air Force. However, for this study the naval domain was selected as main testbed. The Operational School of the RNLN (Opschool) is concerned with the training of tactical decision-making. Students master this task by learning tactical theory and practicing tactical decision-making. The training consists of repeated practice of tactical decisions in order to improve these decisions. For this training the Opschool uses a semi-automated system called the Action Speed Tactical Trainer (ASTT), which can simulate the command central of a military ship in a naval battle, see Figure 1.3.

For training tactical decision-making using the ASTT humans are required, because the reactions of opponents and other parties to the actions of the students have to be programmed during the exercise. The aim of our study it to develop methods and techniques for modeling intelligent, cognitive agents whose behavior does not need to be programmed, but that can *autonomously* act in response to the student. The Opschool was supportive of this goal: they delivered the domain experts required for the elicitation of task knowledge for some of the cognitive models of the agents developed, as well as for the validation of the behavior of these agents.

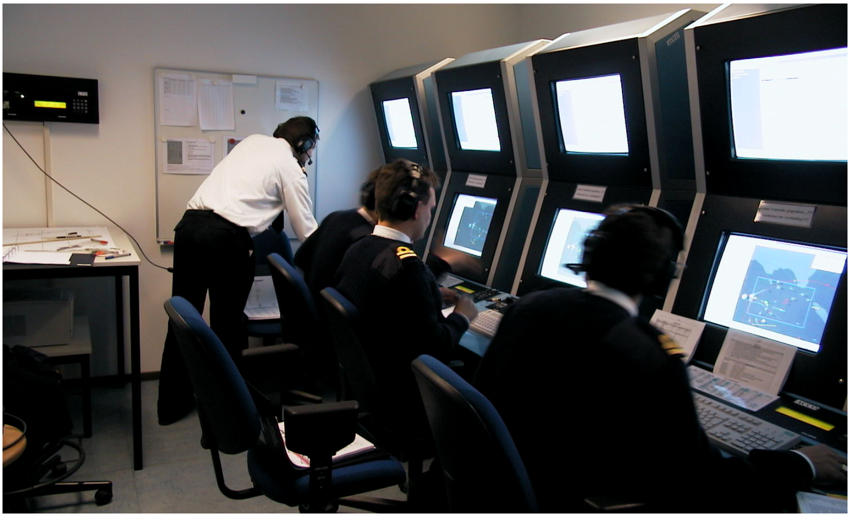

Figure 1.3: Students are trained in naval warfare using the Action Speed Tactical Trainer

1.4.4 Agent Requirements for the Research Task

In this study, we explicitly focus on the modeling of the cognitive processes involved in situational assessment.

Displaying Human-Like Behavior

For agents that participate in the simulation and should be able to perform the situational assessment task as, e.g., a team member or opponent, many aspects need to be modeled. The agent needs to have facilities to:

- observe relevant information in the simulated world;
- interpret the observed, possibly uncertain, information;
- represent that interpretation, e.g., in the form of a belief;
- store interpretated information, i.e., some kind of memory;
- retrieve information from this memory;
- integrate information from different sources or over time;
- infer new information (beliefs) from current information (beliefs);
- be pro-active, e.g., by incorporating goals;
- form and adapt goals based on new information;
- decide which of its goals to pursue;
- decide on, i.e., plan, actions to reach a goal;
- perform actions in the simulated world.

These listed processes are minimally required for situational assessment: they all need to be modeled to enable a software agent to execute that task. In addition, for modeling human-like behavior that is not necessarily rational, some of the following aspects should be modeled:

- how expectations influence the sensing of information or the formation of beliefs;
- how emotions influence the formation of beliefs or the decision on a course of action;
- how cognitive limitations influence the retrieval of beliefs or the execution of (heuristic) reasoning rules;
- how stress / exhaustion / workload has effect on these cognitive limitations and thereby influence the sensing of information, the formation of beliefs, or the decision of a course of action.

This list is not complete: more cognitive aspects, and a multitude of cognitive processes influenced by them can be listed. Fortunately, in order for a software agent to display human-like behavior, in the sense that that is not always rational, it is not required to model all these aspects and how they influence cognitive processes. The modeling of a specific aspect, e.g., expectations, can suffice to create biased behavior.

In the current study we focus on a subset of these aspects and leave others, like emotions, out. In particular, we examine the modeling of biased behavior by focusing on cognitive limitations, and on the circumstances under which these limitations especially bias behavior, e.g., when people are stressed or cognitively exhausted. Moreover, we investigate the influence of these aspects on a number, and not all, of the cognitive processes listed. In this dissertation, we start with the modeling of possibly biased behavior for the interpretation of observed information, for the integration of the resulting beliefs, and for the deduction of new beliefs from others. These processes are amongst the ones most relevant for executing the situational assessment task. Next, we focus on the modeling of possibly biased retrieval of information from memory, a process initially left out. Last, we model a control mechanism for possibly biased belief deduction, as well as control mechanisms for biased decision-making on actions in order to reach a goal.

Providing Feedback to Human Behavior

For providing feedback to a student performing the situational assessment task, an agent needs to be able to reason about the cognitive processes required to perform the task. In particular, an agent has to have access to expert task knowledge, and to knowledge about the type of errors that students typically make (instructor knowledge). In addition, it must be able to observe the behavior of the trainee, and to compare these observations with the behavior of the expert and with typical errors. After diagnosing the trainee's task performance the agent should be able to provide feedback to the student. Last, it would be beneficial if it can store its diagnosis, so that over time it can also generate feedback on the overall task performance.

1.5 Dissertation Outline

This dissertation consists of eight chapters. Chapters 1, 2, and 8 are umbrella chapters in the sense that they respectively introduce, discuss related work to, and discuss and conclude the research that is described in Chapters 3 to 7. Each of these five chapters includes an introductory part and one to four papers. In this section we elaborate on the content of the chapters, and list the papers embedded in them.

1.5.1 Chapter Overview

In the current chapter, **Introduction**, we have discussed the general motivation for this study and listed the three research questions we aim to answer. In addition, we elaborated on the context of this study and on the military research domain, and introduced a specific military task as research example. Moreover, we introduced the regulative research cycle as the research methodology that this study follows. The chapter's first sections denote the *problem definition* of our main regulative cycle, and started with a formulation of the problem and the development of a solution for it.

Chapter 2, **Related Research**, discusses related research which helps to further *diagnose* the research problem. We elaborate on Cognitive Science as well as Artificial Intelligence research concerning the modeling of (biased) cognitive behavior. In addition, we discuss research concerning the generation of feedback.

Chapters 3 to 7 all embed a regulative sub-cycle. The chapters 3, 4 and 5 investigate the phases *a* of the main regulative cycle. Chapter 6 brings about phases *b*, while chapter 7 focuses on phases *c* of the main regulative cycle.

Chapter 3, **Belief Component**, starts with an introductory section in which we elaborate on the research problem, diagnosis, and plan concerning a cognitive agent's belief maintenance capability for situational assessment tasks. In the following section this plan is worked out which leads to a formal belief framework for cognitive agent models, which use is demonstrated in a simple case study (Heuvelink, 2007). Next, this framework is used to develop a formal task model of a realistic military task. This task model is implemented in the cognitive architecture ACT-R which results in the cognitive agent BOA (Heuvelink and Both, 2007) that is subsequently validated (Both and Heuvelink, 2007). The generality of the belief framework and task model are tested by a reimplementation of the model in the Soar cognitive architecture, which results in the cognitive agent Boar (Muller et al., 2008).

Chapter 4, **Memory Component**, introduces a memory capability for an agent incorporating the developed belief framework of Chapter 3 enabling it to store, retrieve, and make inferences on its beliefs. For this, we first develop a method to perform arbitrary aggregations on these beliefs (Heuvelink et al., 2008b) which is later incorporated in the memory model. The memory model supports an agent in performing human-like (biased) reasoning as well as rational reasoning (Heuvelink et al., 2008a), among others by introducing an availability value for beliefs.

Chapter 5, **Control Component**, starts with an introductory section in which we discuss several control aspects for cognitive agents. In the following section we introduce a formal control method that determines the kind of reasoning behavior (biased versus rational) an agent shows. This is not necessarily fixed, but can change dynamically over time due to internal and external aspects (Heuvelink and Treur, 2008). In the next section, we elaborate on an information acquisition component that determines whether an agent senses or tries to remember required information (Heuvelink et al., 2009a). For this research we performed an experiment to deduce human information acquisition behavior in a simple task. The experimental data served as inspiration for the modeling of various task strategies, and was used to evaluate the developed information acquisition model.

Chapter 6, **Cognitive Agents Capabilities**, introduces our idea to facilitate the reuse of components of cognitive agents by tagging them with descriptions of the cognitive capabilities they embed (Heuvelink et al., 2009b). The preliminary Capability Description Framework (CaDeF) proposes a method to describe cognitive capabilities which is demonstrated by describing two generic ones: reasoning and decision-making. In addition, CaDeF is used to describe specific instantiations of these two generic capabilities in an implemented agent, namely BOA (Both and Heuvelink, 2007).

Chapter 7, **Feedback System**, introduces a multi-agent-based feedback generating system developed to generate cognitive feedback to the behavior of trainees in open, complex tasks. The diagnosis capacity of the feedback generating agent is evaluated by letting it diagnose student agents (Heuvelink and Mioch, 2008).

Chapter 8, **Conclusion**, sums up the research and discusses its relevance and significance in relation to the motivation and research questions established in the current chapter. In specific, we address the points of the *evaluation* phase, namely whether the research aids in the future modeling of agents that 5a) can show valid, human-like behavior with a tunable degree of biasedness in complex military tasks, 5b) are affordable because they are based on components that can be found for reuse, and 5c) can give feedback on (biased) trainee behavior in complex military tasks.

1.5.2 Embedded Papers

- Heuvelink, A. (2007). A belief framework for modeling cognitive agents. In *Proceedings of the 8th International Conference on Cognitive Modeling (ICCM 2007)*, pages 235–240. Psychology Press.
- Heuvelink, A. and Both, F. (2007). BOA: A cognitive tactical picture compilation agent. In *Proceedings of the 2007 IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT 2007)*, pages 175–181. IEEE-CS Press.
- Both, F. and Heuvelink, A. (2007). From a formal cognitive task model to an implemented ACT-R model. In *Proceedings of the 8th International Conference on Cognitive Modeling (ICCM 2007)*, pages 199–204. Psychology Press.
- Muller, T. J., Heuvelink, A., and Both, F. (2008). Implementing a cognitive model in ACT-R and Soar: A comparison. In *Proceedings of the 6th International Workshop on From Agent Theory to Agent Implementation (AT2AI-6 2008) in conjunction with AAMAS 2008*.
- Heuvelink, A., Klein, M. C. A., and Treur, J. (2008b). A formal approach to belief aggregation. In *Proceedings of the 12th International Workshop on Cooperative Information Agents (CIA 2008)*, volume 5180 of *Lecture Notes of Artificial Intelligence*, pages 71–85. Springer-Verlag.
- Heuvelink, A., Klein, M. C. A., and Treur, J. (2008a). An agent memory model enabling rational and biased reasoning. In *Proceedings of the IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT 2008)*, pages 193–199.
- Heuvelink, A. and Treur, J. (2008). Controlling biases in demanding tasks. In *Proceedings of the 30th Annual Conference of the Cognitive Science Society (CogSci 2008)*, pages 1392–1397. Cognitive Science Society.
- *An extended version of the paper:* Heuvelink, A., Klein, M. C. A., and Lambalgen, R. L. C. v. (2009a). Modeling human information acquisition strategies. In *Proceedings of the 31st Annual Conference of the Cognitive Science Society (CogSci 2009)*. Cognitive Science Society. *In print*.
- Heuvelink, A., Mioch, T., and Doesburg, W. A. v. (2009b). CaDeF: Towards a method for describing cognitive agent capabilities. *Unpublished*.
- Heuvelink, A. and Mioch, T. (2008). FeGA: a feedback generation agent. In *Proceedings of the 2008 IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT 2008)*, pages 567–572.

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